The MIT/Marine Industry Collegium
Opportunity Brief #23

Progress in Underwater Telemanipulator Research

A Project of
The Sea Grant College Program
Massachusetts Institute of Technology
MITSG 81-4

The MIT/Marine Industry Collegium

PROGRESS IN UNDERWATER TELEMANIPULATOR RESEARCH

Opportunity Brief #23

Revised Edition

July 1, 1981

Marine Industry Advisory Services

MIT Sea Grant Program

Cambridge, Massachusetts 02139

Report No. 81-4

Index No. 81-604-Mni

PREFACE

This Opportunity Brief and the accompanying Workshop held on January 28-29, 1981 were presented as part of the MIT/Marine Industry Collegium program, which is supported by the NOAA Office of Sea Grant, by MIT and by the more than 100 corporations and government agencies who are members of the Collegium. The Workshop was held to provide Collegium members an opportunity to discuss this topic with the faculty and students involved in the research outlined herein. The program of the Workshop is given in the Appendix.

Through Opportunity Briefs, Workshops, Symposia, and other interactions the Collegium provides a means for technology transfer among academia, industry and government for mutual profit. For more information, contact the Marine Industry Advisory Services, MIT Sea Grant, at 617-253-4434.

The underlying studies at MIT were carried out under the leadership of Professor Thomas B. Sheridan, but the author remains responsible for the interpretations and conclusions presented herein.

Norman Doelling

July 1, 1981

TABLE OF CONTENTS

1.0 Business Perspective

Underwater telemanipulators have been defined as "general purpose submersible work vehicles, controlled remotely by human operators having video or other sensors, power propulsion actuators for mobility, mechanical hands and arms for manipulation and possibly a computer for a limited degree of control autonomy" (Reference 1). As a long-term goal, research activities at MIT and at the Naval Ocean Systems Center are directed toward the construction and operation of an underwater, unmanned, untethered telemanipulator. This ideal aim, which may or may not be achieved, helps to focus research on all the significant problems that might attend lesser objectives. For example, the problems of controlling manipulators on a manned submersible or a tethered vehicle are subsets of the more general, more difficult problem of controlling manipulators on a remote, untethered, unmanned vehicle. Thus, the research discussed here should be applicable to both present-day and future vehicles.

Since our workshop on telemanipulators in September 1979, work at MIT has focused on three activities. First, there has been the joint effort to design, develop, and construct the NOSC manipulator and its supervisory control system. Supervisory control system hardware consisting of two PDP-11/23 computers, one on the surface and one on the remote vehicle, has been purchased. Appropriate interface systems have been designed and developed. Almost identical systems were built at NOSC and at MIT so software developed at one place can be easily transferred to the other.

A second effort has been devoted to improving the hardware and software for the supervisory control system (Superman, Reference 2) of MIT's laboratory manipulators. With the improvements, extended experiments on supervisory control can be carried out. Investigations are being conducted on operator performance in manipulating objects that are moving relative to the operator. These experiments can be run with or without a motion compensation system in the control loop.

Experiments were also carried out with an operator observing the work task through a limited bandwidth video system. The operator's controls allowed him to vary picture frame rate, resolution, and gray scale within the constraint that bandwidth held constant. The objective was to see how human operators would trade off among these parameters to maximize their performances.

In the third major effort, observation and manipulation activities in the sea have been simulated through the use of a small vehicle that carries a video camera around the MIT man-machine laboratory. The vehicle has five degrees of freedom: two in a horizontal plane (x,y), vertical motion (z axis), rotation about the z axis, and a pitch or tilt motion for the camera.

The work at NOSC has been sponsored using NOSC Independent Exploratory Development Funds, by the Research and Development Office for OSC Oil and Gas Operation of U.S. Geological Survey and the Office of Naval Research. At MIT research has been supported by the Office of Naval Research and by the NOAA Office of Sea Grant. Formal and informal cooperation among the sponsors has fostered, and been fostered by, the productive, cooperative collaboration between MIT and NOSC principal investigators.

2.0 Improvements in the NOSC Submersible System - EAVE WEST

2.1 EAVE WEST Vehicle

The basic EAVE WEST vehicle is described in our earlier Opportunity Brief (Reference 3) and other publications (Reference 4). A more complete and up-to-date description is given in Reference 8. In the past fifteen months, a number of improvements in the vehicle have been made. The control system has been improved so the NOSC manipulator, discussed below, can be efficiently used on the vehicle in a supervisory control mode. Development of a fiber-optic data communication system has continued (Reference 10, 11).

The vehicle itself is a test bed for application of advanced supervisory control of a deep ocean work system. The control system will involve two computer systems, one located on the surface and one located in the vehicle. Such supervisory control systems allow better control of a remote work system, while permitting very narrow bandwidth control signals between the remote vehicle and the human operator. These concepts are elucidated in Sheridan and Verplank's "Human and Computer Control Undersea Teleoperators" (Reference 1).

The vehicle has been modified significantly to accomodate the new manipulator and the attendent increased payload. More batteries will provide longer operation and additional buoyancy has been added. The fiber-optic interfaces are being developed, a TV camera has been included, and a film camera, which takes both still and moving pictures, is on board. A magnetic, pipe-following instrument package is being developed.

2.2 NOSC Manipulator

The NOSC manipulator system has been designed to be operated underwater in a supervisory control mode. Adaptation to supervisory control was the most important criterion in the manipulator design, but since it was to be used on EAVE WEST, light weight was also an important consideration. The arm now being mounted on the vehicle will be able to lift a six pound load. The system, shown in Figure 2.1, has five degrees of freedom. Although a sixth degree of freedom was considered, weight and control system implementation prohibited it.

Large electric motors drive two degrees of freedom at the "shoulder", while three smaller motors power the "elbow", and provide two degrees of freedom at the "wrist". A separate actuator opens and closes the "jaws" or the "hand". All motors are DC, oil filled, and pressure compensated. Harmonic drives provide high gear ratios to provide easily controlled position and velocity. Each degree of freedom has a potentiometer for position feedback.

A complete description of the manipulator is presented in Reference 9.

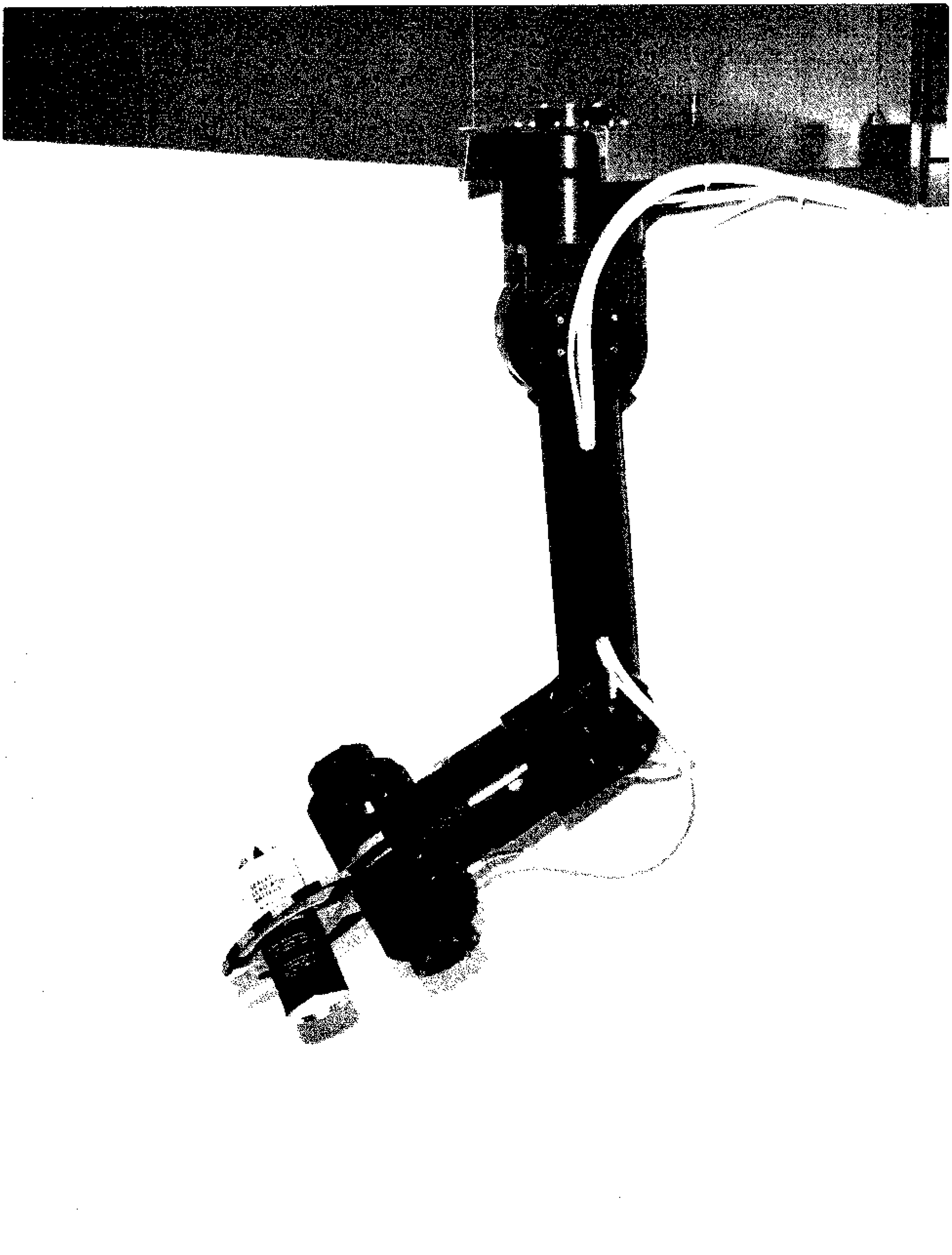


Figure 2.1 The NOSC Manipulator System

3.0 Improvements and Experiments in Supervisory Control at MIT

3.1 Motion Compensation

Two interesting problems have been addressed experimentally during the past year. The first concerns operator performance in situations where the work task moves with respect to the observer (or vice versa). This situation is typical of that encountered when currents or eddies are present, and the work vehicle moves with respect to the work site or work piece. A motion compensation system can be introduced in the telemanipulator control loop to isolate the operator's motions relative to the work from the motions of the work piece. Such a motion compensation system has been hypothesized to greatly assist the operator. MIT investigators have designed a motion compensation system and have run some preliminary experiments to test this hypothesis.

The compensation system is described in Reference 5. Experiments were run by placing the work piece on a moving table driven by periodic motions in three dimensions. Three kinds of experiments were conducted: moving pegs around a series of holes, valve turning, and rectangle tracing. The operator in each case was asked to accomplish certain tasks under three experimental conditions:

1. no table motion
2. table motion with compensation
3. table motion with no compensation

The experimental results showed that compensation substantially reduced the time needed to accomplish most tasks when compared to the time taken with no motion compensation. A typical experimental result is shown in Figure 3.1.

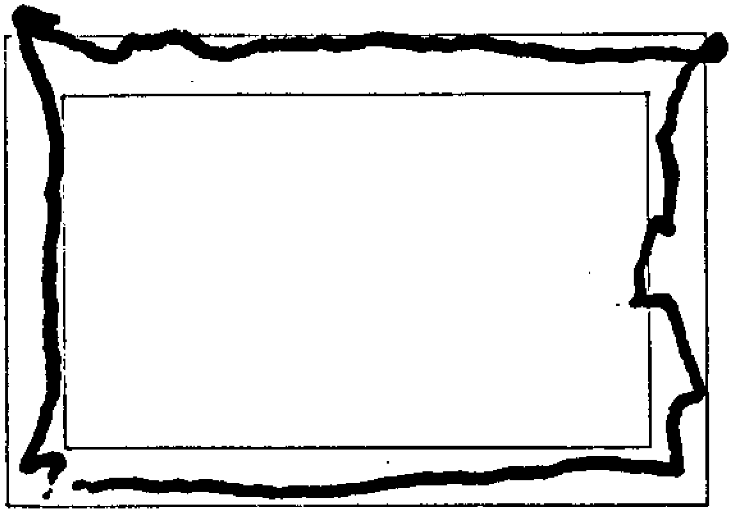
A detailed explanation of the experiments and the results is given in Feference 5. Motion compensation was also effective for peg-in-hole tasks, but did not noticably improve the performance for valve turning experiments.

3.2 Limited Bandwidth Video Experiments

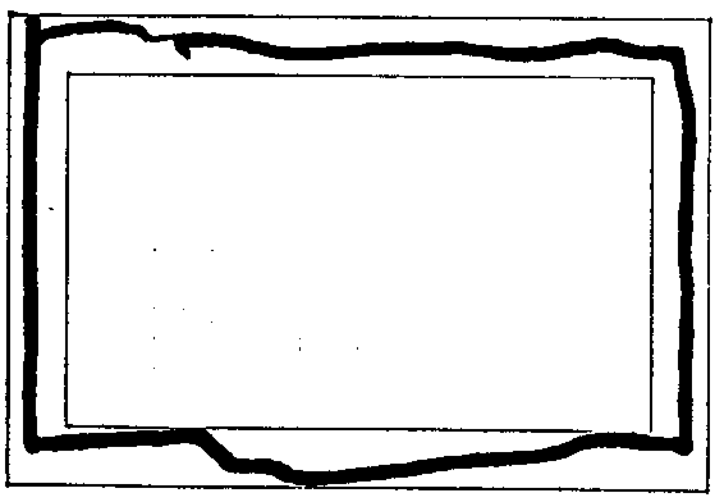
Acoustic links have narrow bandwidth compared to that required for manual video; therefore, operator performance when viewing narrow band TV should be investigated.

The bandwidth required to transmit video signals depends upon the rate at which new pictures are presented (frame rate), the resolution or number of picture elements (pixels), and the number of shades of gray. Fesolution is the number of independent picture elements or dots that make up the scene. This quantity is often expressed as the number of lines in a frame since the number of pixels per line is the same as the number of lines in a square frame. Gray scale is usually the number of levels into which the continuous intensity spectrum is quantized, expressed as the number of binary digits required. A gray scale of one corresponds to black or white; a gray scale of three includes eight shades of gray. For commercial television the frame rate is thirty frames per second. The picture contains 512 lines each having 512 pixels

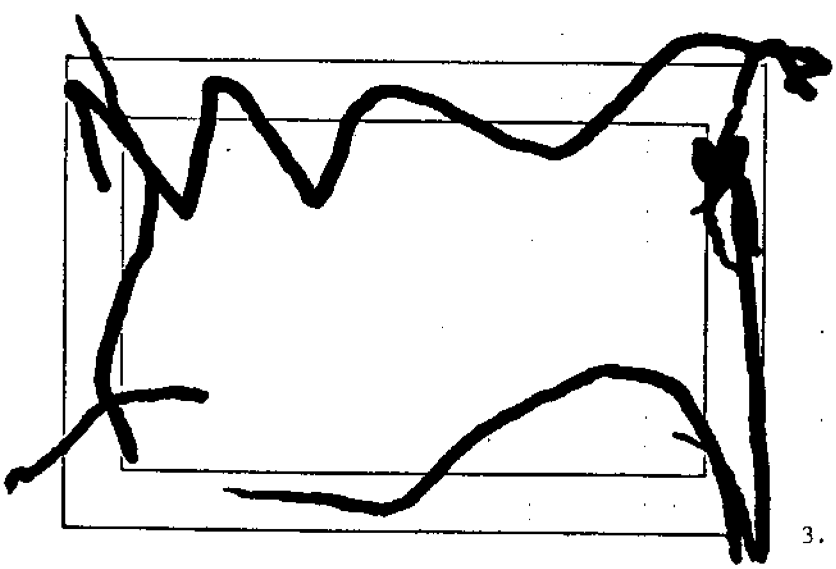
Figure 3.1 Examples of Rectangle Tracing



1. No table motion



2. Table motion with compensation



3. Table motion with no compensation

with 64 levels of gray (6 bits) per pixel, so the total bit rate necessary is 6 x 512 x 512 x 30 or about 47 million bits per second.

When the bandwidth is limited, one or more of the parameters above must be reduced. A special purpose system called Spox was designed to convert television pictures from 128 x 128 pixels per frame with eight levels of gray scale and approximately 30 frames per second into an analogue video signal with frame rates, resolutions and gray scales that were switch selectable.

Subjects were asked to carry out certain master/slave manipulator experiments, observing the manipulators only through the limited bandwidth video system. The maximum bandwidths permitted in the experiments were 10,000 or 20,000 bits per second, one thousand times less than a standard video picture. The fact that subjects were able to accomplish any work with such limited bandwidth is interesting in itself.

The experiments were "peg-in-hole" and "nut-removal" tasks. The experiments themselves were limited and can hardly be described as definitive, but they did clearly indicate that for different types of tasks, operators selected different combinations of frame rates, resolution and gray scale. Switching among the combinations during a single task did not seem to be an essential or desirable facility on all occasions. The operations required to change among the combinations sometimes seemed to interfere with the task at hand.

In summary, the experiment has shown that work can be done at very low bit rates and that some operator preferences depend on the task at hand. Further experiments and refinement of the equipment are needed to more clearly define the potential of this approach. Interested readers are referered to the more complete report (Reference 6).

4.0 Development of a Simulation Vehicle

Simulation systems have been used for years in the aircraft industry to train pilots and investigate human performance with different control systems. The advantages of simulation are many. Training and experiments can be carried out at much lower cost and with much less risk to lives and equipment. In addition, changes in control parameters can be rapidly accomplished by altering software rather than rebuilding the vehicle.

In the commercial unmanned vehicle business, such simulators are not yet used even though the advantages are the same as for aircraft (a visit to DSRU simulator was part of the Workshop program). When a customer purchases equipment, he receives some initial training with it in a shallow tank but afterwards all training is "on the job". For experimental research, simulators are essential for "trying out" new control concepts and for providing a realistic environment in which to carry out tasks under controlled experimental conditions.

A first step in simulation of an undersea vehicle is a small experimental vehicle (EV) having five degrees of freedom. EV has three wheels which are driven by stepping motors. The wheels can rotate $\pm 90^{\circ}$, about the vertical axis, are coupled so that they are always parallel to one another, and allow translation motion in any direction in a horizontal plane. A rotating platform and mast carried above the wheels permit panning of the T.V. camera carried on the mast. A separate motor is provided to raise and lower the camera, while another stepping motor can tilt the camera $\pm 45^{\circ}$ from horizontal. The basic specifications are given in Table 4-1.

	Range	Rate
Translation	----------	0-6 cm/sec
Steering	±90 deg	0-30 deg/sec
Camera up & down	60 cm	0-5 cm/sec
Camera panning	180 deg	0-9 deg/sec
Camera Tilting	±45 deg	0-6 deg/sec
Weight	20 kg	
Size	125 cm(H), 60 cm(W), 60 cm(D)	
Power	AC 115 V	

Table 4-1 Experimental Vehicle Specifications

The preliminary control system configuration is shown in Figure 4.1. The PDP-11/34 translates the signals from the control consoles into pulse strings for driving the appropriate stepping motors on the EV. The left hand joy stick controls the vehicle motions and the right hand control stick operates the camera height, tilt, and pan. The switches on the console provide different control modes. For example, FORWARD on the joy stick can correspond to the vehicle direction in one mode, or to the camera direction in another mode.

The vehicle has already been used in some contour following experiments for which a small set of position probes were added to the vehicle. These simple sensors were used to keep the EV a fixed distance from the object and also provided a method of detecting radius of curvature. The experimental layout and a simple demonstration plan are shown in Figures 4.2 and 4.3. This configuration was used in experiments that compared performance of the system under direct manual control by the operator with its performance under supervisory control for a simple inspection task. This work is described more completely in Reference 7.

In the next extension of this project, which is already underway, a very general model for the dynamic characteristics of real undersea vehicles will be inserted in the control system. The model will accept signals from the joy stick and will output control signals to the wheels in a manner described by the physics of the submersible under study. The object is to have the laboratory vehicle respond to the control stick motion in essentially the same way as the undersea vehicle. Inertial forces, drag, moments of inertia, cross-coupling between rotation, and translation motions and the like all can be entered in the digital model. Currents, turbulence, and other natural phenomena can also be included in the control loop. In addition, time delays can be introduced to represent control under untethered conditions in which sonic links might be used.

If the response of the simulation vehicle correlates well with the response of an actual vehicle, the simulation system will be a very powerful tool for laboratory investigations and for training personnel using RCVs. The correlation will be tested using parameters in the model corresponding to the physical parameters of the NOSC EAVE WEST vehicle. At a later date we hope to test the simulation system using physical parameters from one or more commercial RCV vehicles.

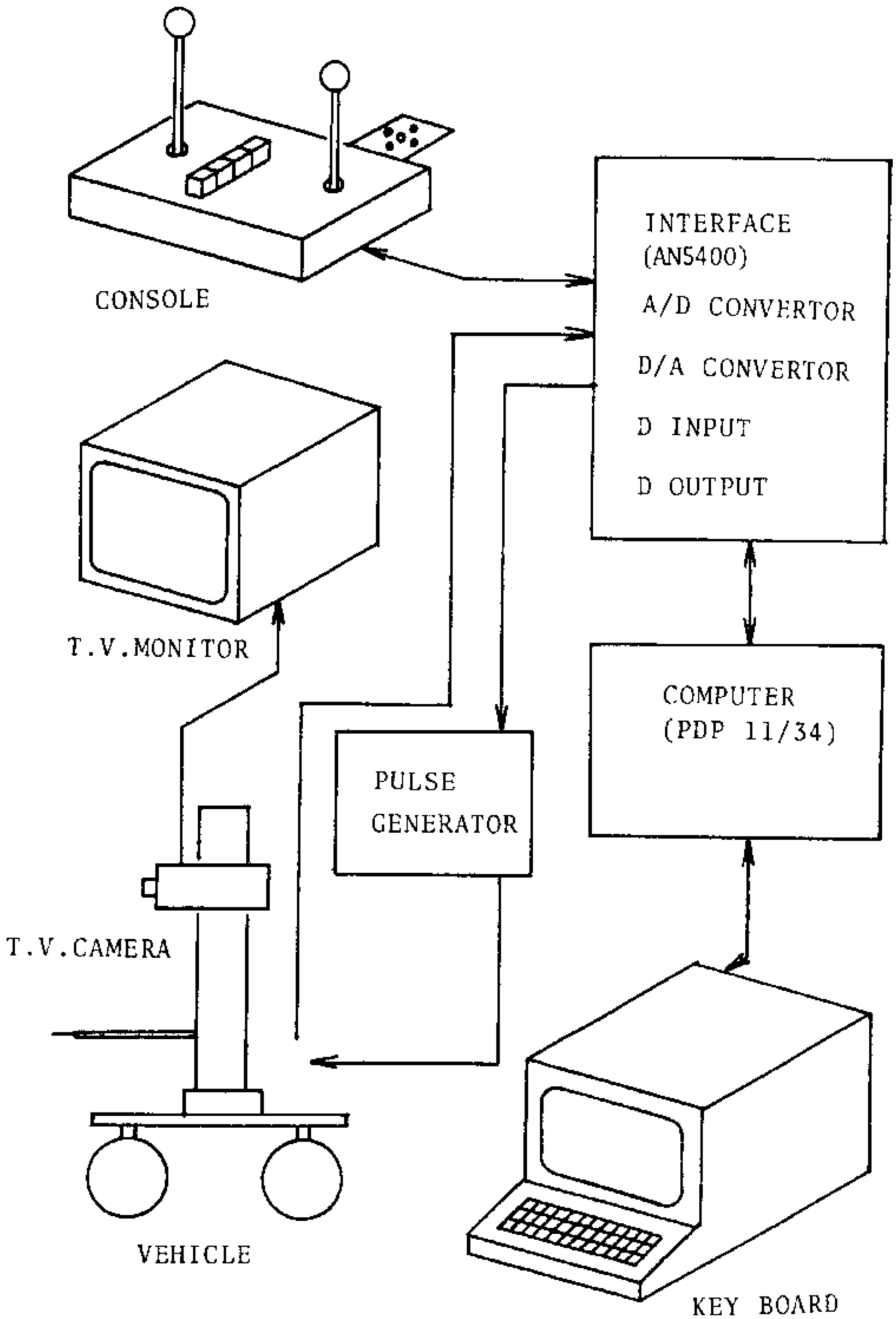


Fig. 4-1 Control System Configuration

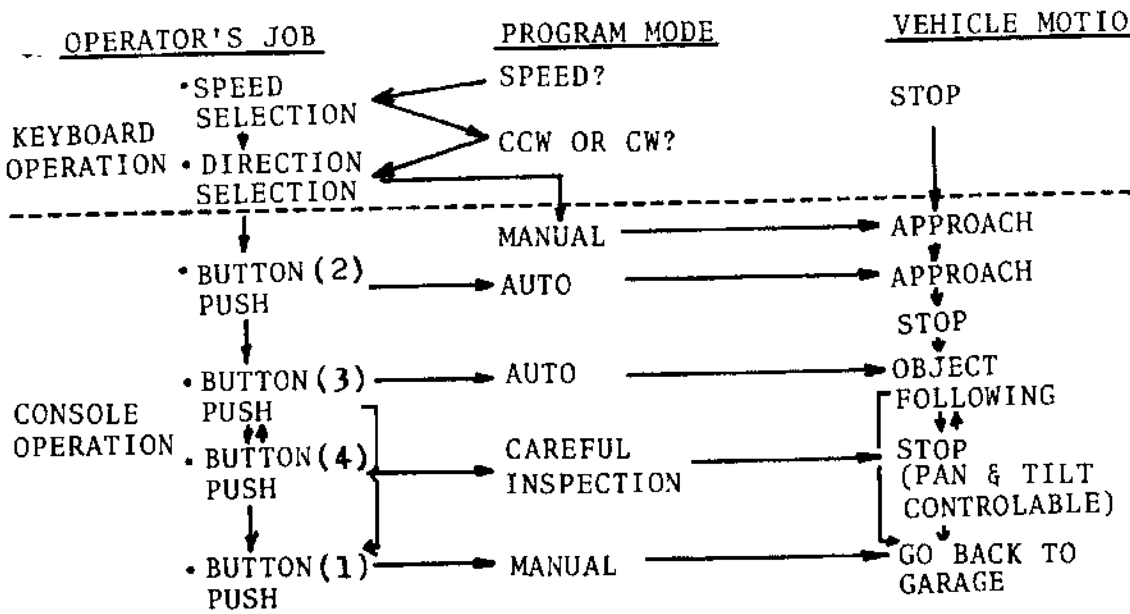


Fig. 4-2 Demonstration Plan

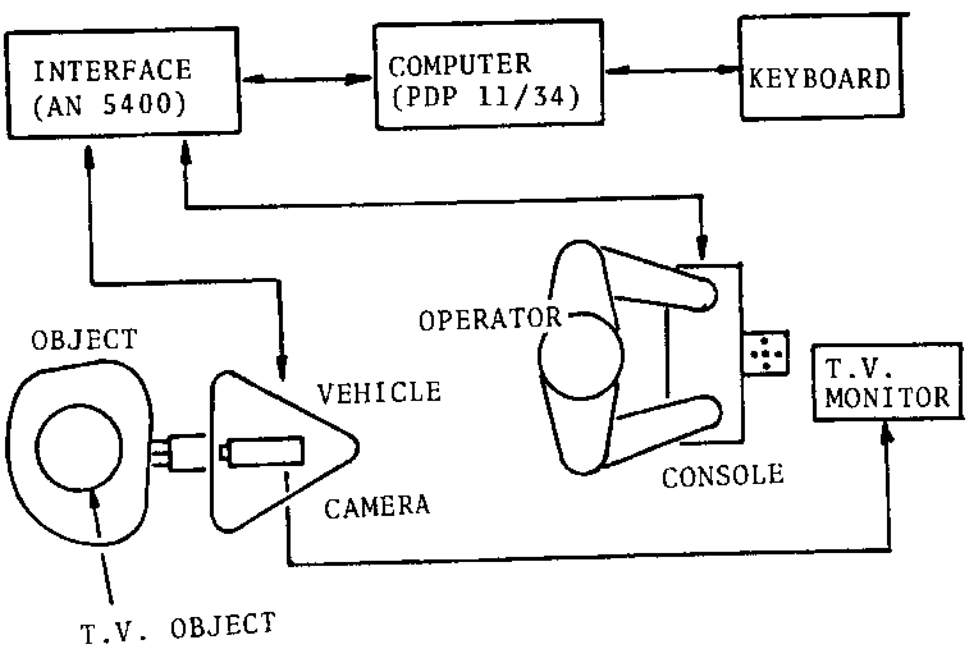


Fig. 4-3 Experimental Layout

5.0 References

1. Sheridan, T.B. and Verplank, W.L., "Human and Computer Control of Undersea Teleoperators," Man-Machine Systems Laboratory Report, Massachusetts Institute of Technology, July 1978.

2. Brooks, Thurston L. and Thomas B. Sheridan, "SUPERMAN: A System For Supervisory Manipulation and the Study of Human/Computer Interactions," Cambridge, MA: MIT Sea Grant Program, 1979 (MITSG 79-20).

3. Doelling, Norman, "Some Federally Sponsored Research Programs for Unmanned Underwater Vehicles," MIT Marine Industry Collegium Opportunity Brief #18. Cambridge, MA: MIT Sea Grant Program, 1980 (MITSG 80-5).

4. Heckman, Paul and H. McCracken, "An Untethered, Unmanned Submersible," in Proceedings of Oceans '79 September 1979: pp. 733-737.

5. Tani, Kazuo, "Supervisory Control of Remote Manipulation with Compensation for Moving Target," Man-Machine Systems Laboratory Report, Massachusetts Institute of Technology, July 21, 1980.

6. Deghuee, Bradley James, "Operator-Adjustable Frame Rate, Resolution, and Gray Scale Tradeoff in Fixed-Bandwidth Remote Manipulator Control," Man-Machine Systems Laboratory Peport, Massachusetts Institute of Technology, September 1980.

7. Odahara, Tetsuichi, "Experiments in Supervisory Control of a Computerized Vehicle for Inspecting Curved Surfaces," Master's Thesis, Department of Mechanical Engineering, MIT, May 1980.

8. Heckman, Paul Jr., "Free-Swimming Submersible Test Bed (EAVE-West)," Naval Ocean Systems Center Technical Report 622. September 1980.

_______ and H. McCracken. "An Untethered, Unmanned Submersible," Proceedings Oceans '79, September 1979: pp. 733-37.

9. Bosse, Peter and Paul J. Heckman Jr., "Development of an Underwater Manipulator for Use on A Free-Swimming Unmanned Subermisible," Naval Ocean Systems Center Technical Peport 632. October 1980.

10. S. J. Cowen, P. J. Heckman, M. Kono, "Fiber-Optic Communication Links for Unmanned Inspection Submersibles," Naval Ocean Systems Center Technical Report 652. October 1980.

11. S. J. Cowen, "Fiber Optic Transmission System Employing Pulse Frequency Modulation," Proceedings Oceans '79. September 1979: pp. 253-59.

6.0 Appendix

MIT/Marine Industry Collegium

Workshop #23

PROGRESS IN UNDERWATER TELEMANIPULATOR RESEARCH

Naval Oceans Systems Center, San Diego, CA

January 28, 1981

1800 Dinner on your own at Half Moon Inn (phone: 714/224-3411)

1930 Informal meeting - Marina Room, Half Moon Inn

Industry/Government Dialogue

Sponsors of the research from NOSC, USGS and Sea Grant will speak briefly on their mission objectives and related research. Industry members will be asked for comments and suggestions concerning their research interests and needs.

January 29, 1981

0800 Bus will leave Half Moon Inn for NOSC

0845 Welcome and Introduction

Norman Doelling, MIT Sea Grant
Howard Talkington, Head, Ocean Technology Department, NOSC

0915 Experiences with Work Systems in the Ocean Environment

Robert L. Wernli, Project Engineer for Work System Package, NOSC

1000 Discussion

1015 Coffee Break

1030 Progress in Supervisory Control: Vehicle Simulators; Future Research Directions

Professor Thomas B. Sheridan
Mechanical Engineering Department, MIT

1130 Discussion

1145 Luncheon

1300 Work System Needs at 18,000 feet for the Ocean Margin Drilling Program
Walter Gray, President, Diverless Systems, Goleta, CA

1345 The NOSC/USGS Free Swimming Submersible - EAVE/West
Paul Heckman, Head, Applied Science Research, NOSC

1430 Discussion

1445 Supervisory Control System for the NOSC Manipulator
Dana Yoerger, Doctoral Student, Dept. of Mechanical Engineering, MIT

1530 Discussion

1600 Bus will return to Half Moon Inn